Renewable and Sustainable Energy Reviews 32 (2014) 84–99

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Impact analysis of wind farms on telecommunication services

I. Angulo [a], D. de la Vega [a,*], I. Cascón [a], J. Cañizo [a], Y. Wu [b], D. Guerra [a], P. Angueira [a]

[a] Department of Communications Engineering, University of the Basque Country (UPV/EHU), Alda. Urquijo s/n, 48013 Bilbao, Spain
[b] Communications Research Centre, Ottawa, Canada

A R T I C L E I N F O

Article history:
Received 23 October 2012
Received in revised form
21 November 2013
Accepted 29 December 2013
Available online 25 January 2014

Keywords:
Wind farms
Telecommunication services
Impact studies
Radar sysytems
Radionavigation systems
Broadcasting services
Fixed radio links

A B S T R A C T

Wind power is one of the fastest-growing technologies for renewable energy generation. Unfortunately, in the recent years some cases of degradation on certain telecommunication systems have arisen due to the presence of wind farms, and expensive and technically complex corrective measurements have been needed. This paper presents a comprehensive review on the impact of wind turbines on the telecommunication services. The paper describes the potential affections to several telecommunication services, the methodology to evaluate this impact, and mitigation measures to be taken in case of potential degradation, both preventive and corrective. The telecommunication services included in this review are those that have demonstrated to be more sensitive to nearby wind turbines: weather, air traffic control and marine radars, radio navigation systems, terrestrial television and fixed radio links. The methods described in the paper allow a thorough case-by-case analysis before the wind farm is installed, taking into account the particular features of each installation and the involved services. The prediction of the potential impact makes it possible to propose alternative solutions in order to assure the coexistence between the wind turbines and the telecommunication services.

Contents

* Corresponding author. Tel.: +34 946 014 127; fax: +34 946 014 259.
E-mail address: david.delavega@ehu.es (D. de la Vega).

http://dx.doi.org/10.1016/j.rser.2013.12.055

1. Introduction

The assessment of suitability of a certain location for the installation of a wind farm requires the consideration of multiple impact issues: visual aspects, environmental effects such as the impact on wildlife and birds, shadow flicker from wind turbines and noise pollution [1–3]. Electromagnetic effects should also be considered, due to the fact that the presence of a wind farm near telecommunication transmitters or receivers may introduce distortions on the transmitted signals [1]. These distortions can cause different effects on the radiocommunications services depending on several factors such as the frequency band, the modulation scheme and the discrimination of the radiation pattern of transmitter and receiver aerials. The radiocommunication services that have proved to be more sensitive to the presence of wind turbines are the following: Air Traffic Control radars [4–10], weather radars [11–16] and maritime radars [17–21]; aeronautical navigation systems such as VOR [10,22] and ILS [23,24]; fixed radio links [25–27]; and broadcasting services (mainly analog television[25,28–35] and digital television to a lesser extent [25,37–39]).

Although the critical interference cases are not common, if they occur when the wind farm is already installed, the posteriori corrective measurements are normally technically complex and/or cost prohibitive [40–42]. By contrast, the prediction of the potential impact of a wind farm on the telecommunication services before its installation allows the planning of alternative solutions in order to assure the coexistence between the wind turbines and the telecommunication services. This potential impact must be analyzed in a case-by-case basis, taking into account the particular features of each installation and the involved services, such as the accurate location of the wind turbines and the telecommunications infrastructure, terrain altimetry and topography, telecommunication towers height, service frequency and modulation, radiating systems characteristics and reception conditions.

In case of a potential problem being identified, preventive measurements can be taken in order to avoid it. These may include proposing safe-guarding zones, changing the location of a wind turbine in the preliminary design of a wind farm, choosing a model with different dimensions or selecting alternatives for the telecommunication services (new transmitter locations, different communication links, etc.) [1]. Whatever the case may be, the cost of preventive measurements is lower than the one of corrective measurements and prevents public opposition to wind energy development.

This paper presents a comprehensive review on the impact of wind turbines on the telecommunication services, with special dedication to the methodology to be applied in order to detect potential problems before they occur and propose possible solutions. The paper is organized as follows. First, some basic concepts on the electromagnetic effects of wind turbines are introduced in Section 2. Then, the potential affections to the different telecommunication services are presented in the three following sections. Each of these sections includes a brief description of the service, the possible interference effects due to a wind farm, the methodology to evaluate this potential impact, and mitigation measures to be taken in case of potential affection, both preventive and corrective. Finally, the main conclusions are summarized in Section 7.

2. EM effects of wind turbines

At microwave frequencies, when an electromagnetic wave reaches a body, it induces oscillating charges on its surface. These currents produce in turn a scattered wave that re-radiates energy in various directions. The spatial distribution of the scattered energy depends on the size, shape and composition of the obstacle, and on the frequency and nature of the incident wave [43]. The mechanism of the electromagnetic scattering is a complicated process that includes reflections, diffractions, surface waves, ducting, and interactions between them [44]. In this context, the total field at an observation point due to radiation by induced fields over the surface of the obstacle will be comprised of the direct fields (desired signal) and scattered fields (potential interference).

When the scattering direction is back toward the Source of the radiation, it is called monostatic scattering. By contrast, bistatic scattering is the name given to the situation when the scattering direction is any but the retro-direction. A particular case is forward scattering, which occurs when the bistatic angle is approximately 180° [43]. In general, the forward scattering from an obstacle is stronger than the backscattering. However, the forward scatter is nearly out of phase with the direct field; therefore, it is subtracted from the direct field, creating a shadow behind the wind turbine [43]. As an example, Fig. 1 shows the horizontal and vertical scattering patterns of a wind turbine for certain illumination conditions and static position of the blades.

As observed in Fig. 1, the scattering patterns show great variability mainly due to the complex design of the nacelle and the blades. Moreover, the amplitude of the scattered signal varies with the blade rotation. Fig. 2 shows an example of the time variability of the signal scattered by a wind turbine with rotating blades, obtained from empirical data [38,45]. It can be observed that there is a periodic variation with a repetition period of approximately 1 s, corresponding to 1/3 of the rotation rate of the wind turbine, as expected for a three-blade rotor. Both the mean level and the time variability due to blade rotation are dependent on the orientation of the wind turbine with respect to the transmitter and the receiver.

Furthermore, due to the moving blades of the wind turbine, the frequency of the signal will be shifted according to the Doppler effect. The Doppler frequency shift depends on the radial velocity of the moving object with respect to the receiver. As a consequence, a frequency spread will be caused in the signal spectrum, which will depend not only on the rotation angular speed of the blades, but also on the blade length and on the relative orientation of the nacelle with respect to the transmitter and the receiver.

In summary, a wind turbine may cause a scattered signal of dynamic nature which is both amplitude and frequency modulated due to the rotating blades. The time and frequency characteristics of this scattering signal will depend on multiple factors.

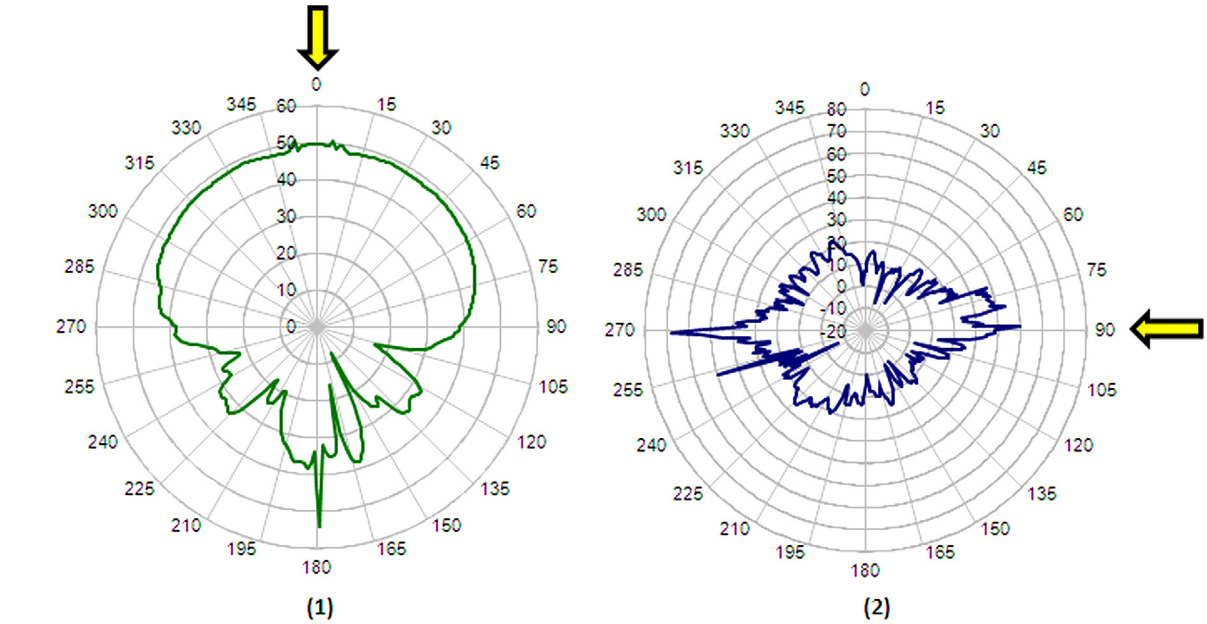


Fig. 1. Example of the scattering pattern of a wind turbine for certain illumination, conditions and position of the blades, where yellow arrows represent the direction of incidence. (1) Horizontal plane; and (2) vertical plane of the scattering pattern. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

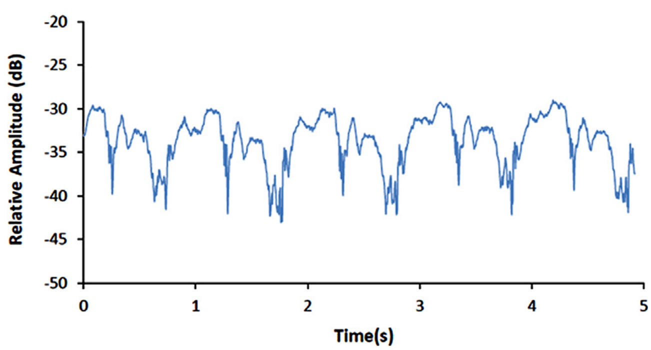


Fig. 2. Example of the time variability of the signal scattered by a wind turbine as blades rotate.

Some of them are fixed, such as the distance from the transmitter and the dimensions and materials of the wind turbine, while other are time-varying, such as the nacelle orientation and the rotation speed of the blades.

3. Weather, Air Traffic Control and maritime radars

A radar is an electromagnetic system for detection, location and recognition of target objects, which operates by transmitting electromagnetic signals, receiving echoes from target objects within its coverage volume, and extracting location and other information from these echo signals [46]. It basically consists of a transmitter to generate the high-frequency signal, an antenna to send the signal out and to receive the echo back from the target, and a receiver to detect the signal. The antenna of the radar usually rotates about a vertical axis, scanning the horizon in all directions around the radar site. Radars equipped with Doppler capability do not only detect and measure the power of the echo received from a target, but they also measure the speed of the target moving toward or away from the radar [47].

According to their specific purpose, several types of radar can be identified. Each of these is designed to detect a specific kind of target, and therefore, they feature different working regimes and frequency bands, operation ranges, etc. Weather radars aim at detecting meteorological phenomena like clouds, rain or storms, while ATC radars aim at detecting aircrafts, and maritime radars at ships and boats. There are different working frequencies ranging from S-band (2.0–4.0 GHz) to X-band (8.0–12.0 GHz) in the case of weather and marine radars, and L-band (1.0–2.0 GHz) and S-band (2.0–4.0 GHz) in the case of ATC radars [48–51].

Weather radars usually work with three main types of data. In the reflectivity mode, return echoes from targets are analyzed for their intensities to establish the precipitation rate in the scanned volume. In the Doppler mode, the precipitation's motion is calculated. Finally, in the polarization operational mode, orthogonal polarization pulses are used to evaluate drop shapes and distinguish amongst different precipitation types, such as rain, snow, or hail [47].

In the case of ATC radars, two main types are distinguished. Primary Surveillance Radars (PSRs) basically work as explained before, detecting the electro-magnetic energy reflected from the body of the aircraft. By contrast, in the Secondary Surveillance Radars (SSRs), the equipment on board the aircraft receives an interrogation from the ground station and cooperates by replying with a signal broadcast of its own that is detected by the radar [9].

With respect to marine radar, it breaks down into two main application areas. The vast majority is used at sea and on navigable waterways by ships and smaller craft; the others are used by port and coastal authorities for vessel surveillance from land-based sites [48].

3.1. Interference effects of a wind farm on radar systems

Wind turbines are huge signal reflectors of greater dimensions than the targets that radars aim at, and therefore, their presence may hide weaker signals from smaller targets. Additionally, the rotating blades generate a Doppler shift also detected by the radars. As current radars are not designed to identify and filter

out signals from wind turbines, significant information in the surroundings of the wind farm may be lost.

In weather radars, wind turbines may lead to the misidentification of thunderstorm features and to the erroneous characterization of meteorological phenomena. These errors may be due to clutter returns (signal echoes from the wind turbines), signal blockage (the physical size of the wind turbine creates a shadow zone behind them) and interference to the Doppler mode of the radar (frequency shifted echoes from the rotating blades) [49]. Fig. 3 shows the blockage of the radar signal by the wind turbine and the shadow volume where the detection capacity is reduced.

Fig. 4 shows a real case of how wind farms are detected by the C-band pulsed Doppler radars of the Spanish weather radar network, where the reflected signals are misinterpreted as rainfall, as analyzed in [52]. Fig. 5 shows an example of how the signals from wind turbines disturb the precipitation level detected by the same radar.

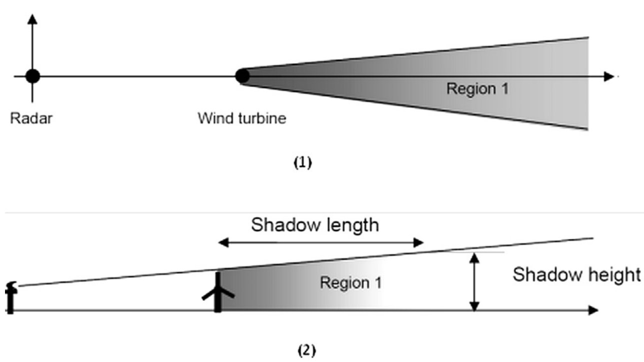


Fig. 3. Blockage of the radar signal by the wind turbine and shadow volume where the detection capacity is reduced. (1) Aerial view; (2) front view.
(*Source*: Eurocontrol [9]).

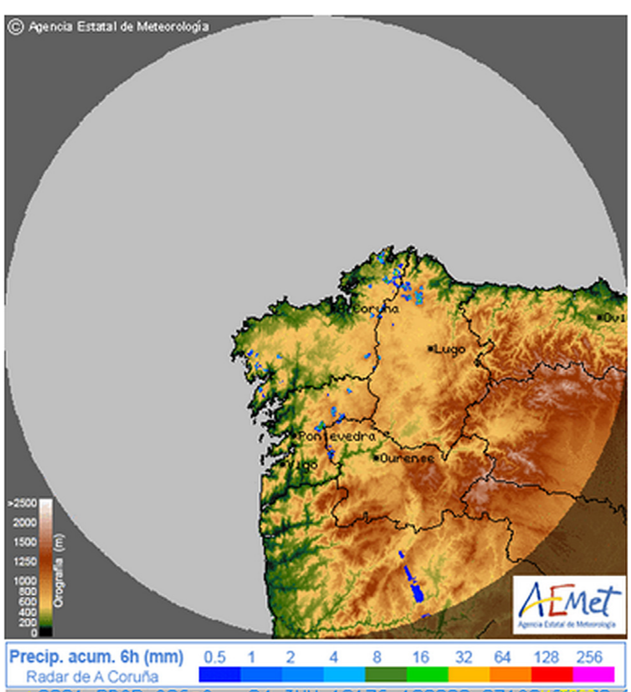


Fig. 4. Six hours accumulated rainfall map estimated by a C-band pulsed Doppler radars of the Spanish, weather radar network, in a sunny day without rain precipitation. Most of the blue colored areas do not correspond to precipitation, but to reflected signals from wind farms.). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
(*Source*: AEMET [78].

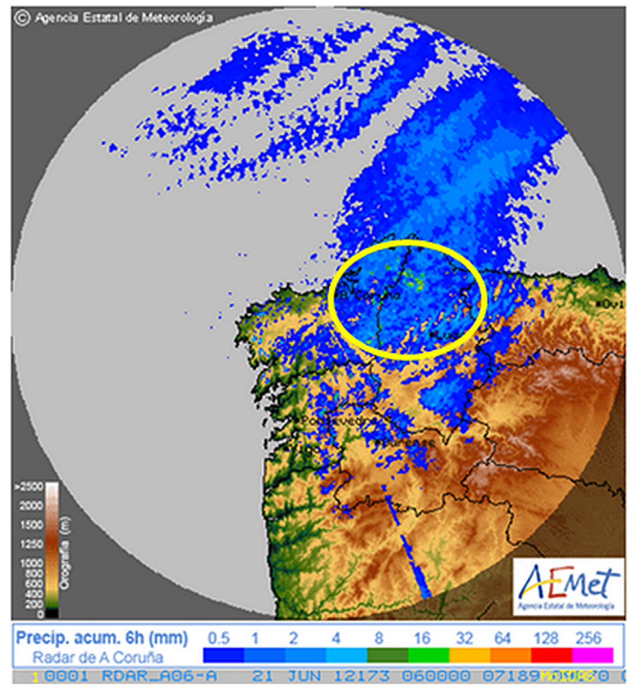


Fig. 5. Six hours accumulated rainfall map estimated by the same radar in case of rainfalls. It can be observed that signals from wind turbines (in green and yelow) increase the estimated precipitation level in the affected area (yellow circle)). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
(*Source*: AEMET [78].

In ATC radars, similar effects can be suffered, leading to false target reports which can have a detrimental impact on the surveillance component of the radar operations, as observed in several cases in Germany and France [53,54]. Similarly, other reports contain numerous examples of the effects of wind farms on ATC radars in the United Kingdom and the United States of America [4,8,55].

With respect to marine radars, both shipborne and shorebased, the large vertical extent of the wind turbine generators might return radar responses that may be strong enough to produce multiple interfering echoes [17–19]. Therefore, echoes of small craft within the wind farm can merge with strong echoes generated by the turbines when the craft pass close to the towers making them invisible to radar observers or automatic plotting facilities. However, while navigating, this effect will only be temporary until the craft moves away from the turbine [18].

3.2. Methodology to evaluate the potential impact of a wind farm on weather radars, ATC radars, and maritime radars

3.2.1. Weather radars

The World Meteorological Organization (WMO) [11] and EUMETNET (an association of national weather services within Europe) [14] define “exclusion distances”, where no wind farms should be installed, and “coordination distances”, where detailed studies should be carried out. More precisely, according to the WMO and EUMETNET, the placing of wind turbines should be avoided at ranges lower than 5 or 10 km (for C and S band radars, respectively) and coordinated with the weather radar operators at distances up to 20 km or 30 km (for C and S band radars, respectively). The studies should consider the characteristics of each wind turbine of the wind farm in order to find reasonable solutions ensuring, in the non-critical zones, a minimal impact on the radars.

Recent studies suggest that the present 20 km upper limit value should be removed because the risk of interference at longer distances than 20 km should not be ignored [41]. In practice, this means that all the wind turbines in line of sight with the weather radar should be analyzed.

Three different scenarios are considered: blocking of the radar beam, clutter and Doppler effect.

3.2.1.1. Blocking of the radar beam. The blocking of the beam occurs when the radar is pointing in direction of the wind turbine and there is direct line of sight between them. If the physical area of a wind turbine blocks part of the radar beam, this obstruction, even if partial, can lead to errors in the precipitation monitoring. Fig. 6 shows an example of assessment of the volume behind the wind turbines where the radar beam is blocked, causing the misidentification of precipitation phenomena.

Typical weather radars transmit the signal to a very limited sector, using antennas with 1°–2° beam aperture (at 3 dB). Evidently, the section of the radar beam increases as the distance from the radar increases. It should be noted that the service range of a weather radar may cover up to 150–300 km, and therefore, geographical areas of significant size may be affected by the blocking of the beam [11]. The degree of the radar beam blocking depends on both the distance between the radar and the turbine and the turbine dimensions, and it is possible to estimate it by calculating the portion of the power density that is obstructed by the physical dimensions of the wind turbine.

Accordingly, in order to evaluate the impact due to the blocking of the beam on the weather radar, the percentage of the beam section blocked by the wind turbine structure should be calculated (see Fig. 7) for the wind turbines located within a distance of 10 km from the radar[11]. To do so, the particular features of the case under study should be considered: terrain height, position of the radar and the wind turbines, physical size of the turbine, volume occupied by the scanning radar beam and the different elevation angles of the radar beam. The value of 10% of blocking of the beam is the acceptable maximum value proposed by the World Meteorological Organization [11]. Most European countries follow this recommendation in their national consultation and approval processes, although there are countries that use more restrictive values, such as the United Kingdom Met Office (1% maximum beam blocking) or Sweden (2% maximum beam blocking) [41]. Other countries, such as Denmark and Germany, only apply a fixed minimum separation distance between the radar and the wind turbines [41].

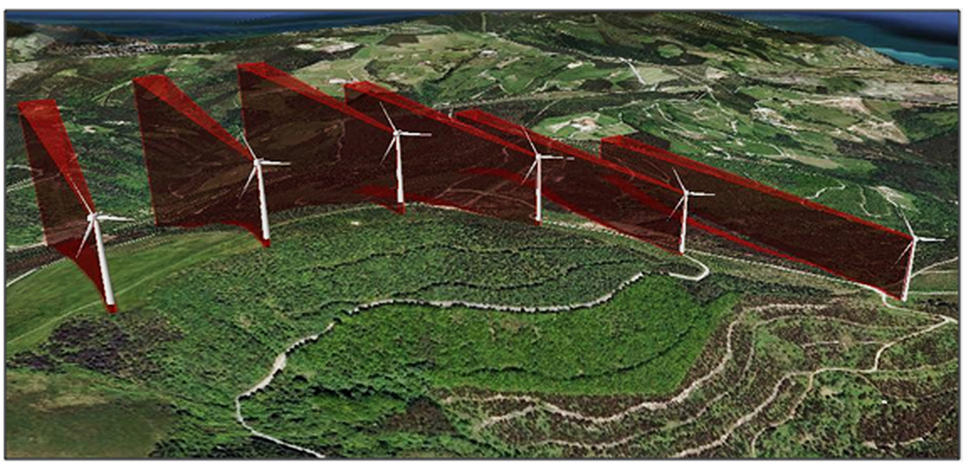


Fig. 6. Blocking of the radar beam and "shadow volume" (in red) generated behind each wind turbine [61]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

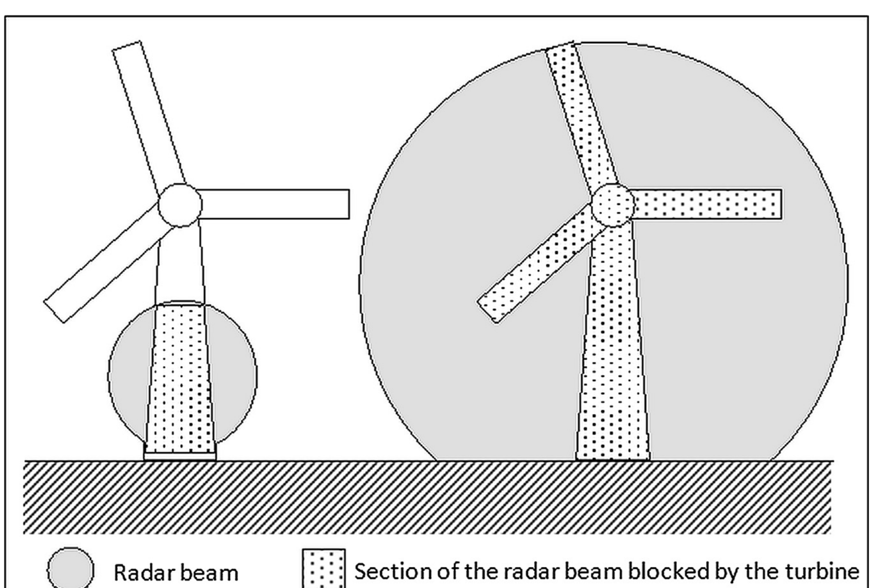


Fig. 7. Example of how estimate the section of the radar beam blocked by a wind turbine.
(*Source*: WMO [11]).

3.2.1.2. Clutter. For radar applications, the power scattered by a target is expressed in terms of its Radar Cross Section (RCS), which is defined as the projected area required to intercept and isotropically radiate the same power as a target scatters toward the receiver [57]. The RCS of a wind turbine depends on fixed parameters as its dimensions and materials, and on variable parameters such as its relative position with respect to the radar and the blades rotation.

The clutter from wind turbines occurs when a radar echo coming from a wind turbine reaches the radar with a power level higher than the radar sensitivity (or lowest power for target detection). The clutter may prevent from correctly detecting the precipitation level in the affected area.

According to WMO [11], the impact of wind turbines on reflectivity operation of weather radars cannot be neglected until distances of about 15 km for C band radars and beyond 30 km for S band radars, mainly if the aggregate effect of multiple wind turbines is considered. Within this area, the clutter returns from wind turbines should be calculated as a function of the radar specifications (operating frequency, antenna gain and radiation pattern, internal losses) and the wind turbine characteristics (RCS and distance to the radar) [48,49]. If the clutter level is higher than the radar detection threshold, the weather information could be affected [11].

The assessment of the clutter returns from the turbines allows to delimit the volume that could be affected by the wind farm (azimuth sector and beam elevations). Fig. 8 shows an aerial view that shows the estimation of the scanning horizontal area where the wind farm will cause significant clutter level in the weather radar.

Most of the radars include signal processing techniques that remove part of the effects caused by the scattered energy from wind turbines. For example, Doppler filters remove static scattering from turbines′ masts. Nevertheless, it must be considered that the scattered energy will increase the effective noise floor of the radar receiver [8], which degrades the detection capacity, and therefore, the data quality obtained by the radar.

3.2.1.3. Doppler. The Doppler mode of a radar is aimed at detecting movement. Therefore, in order to determine the influence of a wind turbine on this operation mode, only the blades should be considered. Furthermore, as previously commented, the radial velocity of the blades depends on the rotation angular speed of the blades and on the relative orientation of the nacelle with respect to the transmitter and the receiver. Hence, it changes according to the wind conditions, and the scattered signal from the wind turbines detected by the radar will be also dependent on weather conditions. The methodology to determine a potential influence is similar to the presented for the clutter analysis, based on the estimation of the power backscattered from the turbines and received in the radar.

WMO [11] and EUMETNET [14] determine that the impact on Doppler detection is the most critical effect in weather radars. In the case of the Doppler detection mode, only the RCS of the moving parts of the turbine (the rotating blades) should be considered. Nevertheless, the detection level is lower in this mode, and detection takes place as soon as the received signal is higher than the noise level [1]. For this reason, WMO and EUMETNET propose to prohibit any installation of wind farms in a radius of approximately 5 km for C band radars, and 10 km for S band radars (taking into account the aggregate impact). Beyond these “exclusion” distances, for C band radars, a “coordination” distance of 20 km seems necessary whereas for S band radars, a “coordination” distance of 30 km would be necessary, acknowledging that 30 km represents approximately the maximum distance for Doppler detection in clear sky conditions without precipitations [11,14].

Fig. 9 shows an example of the radar beam illuminating the turbines of a real wind farm. Red areas represent the portion of the radar beam that impinges on the blades. This calculation allows knowing if the rotating blades affect a specific elevation angle, and which is the section of the blades that may affect the Doppler detection. This assessment is the first step in the analysis of the impact on the Doppler mode, and it determines the beam elevation angles that may be affected and the turbines that are involved in this type of impact.

3.2.1.4. Additional considerations. In addition to clutter returns caused by reflections from wind turbines, backscattered energy from turbulent eddies in the wake of the wind farm may be observed on the radar display, which show similar characteristics to clear-air backscatter from discontinuities in the refractive index. Although these are echoes weaker than those from reflections from wind turbines, they could significantly enlarge the affected radar coverage [49].

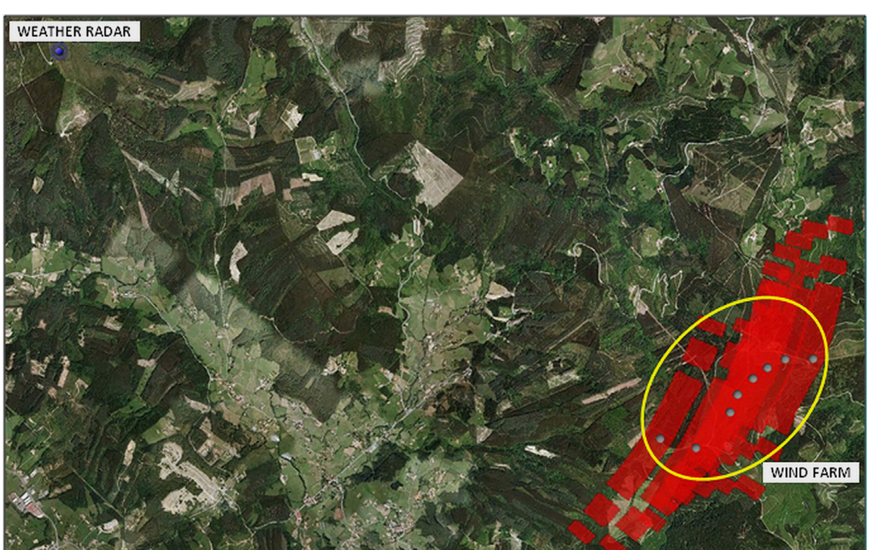


Fig. 8. Example of an aerial view showing the estimation of the scanning horizontal area where the wind farm may cause significant clutter level in a weather radar located at 7.7 km (represented as a blue dot) [61]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

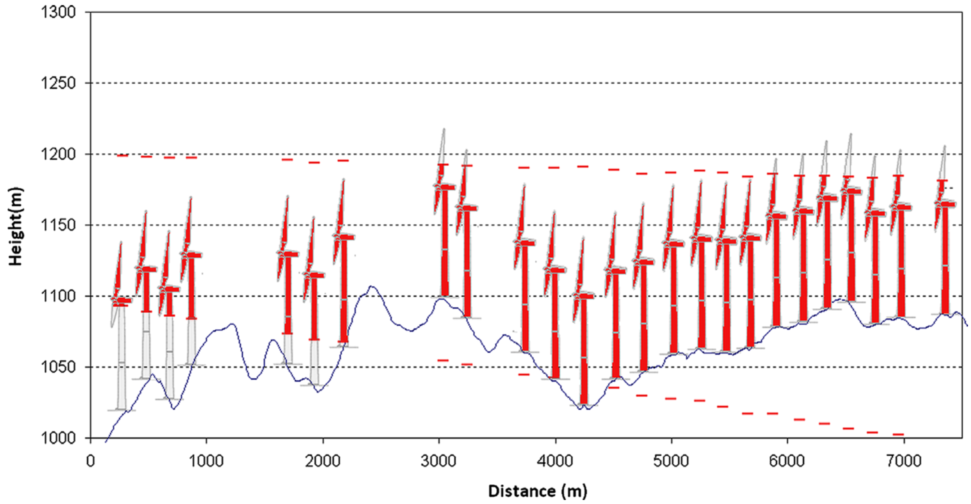


Fig. 9. Example of the radar beam illuminating the wind turbines, indicating the portion of the beam that impinges on the blades. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Clutter and Doppler effects can also occur if the energy transmitted from a side lobe of the radar antenna is reflected from a wind turbine back to the radar. In this case, the azimuth sector that may be degraded is wider, and depends on the directivity of the radiation pattern of the radar antenna. For this reason, not only the antenna nominal gain, but the whole radiation pattern of the radar antenna should be considered in the analysis.

Aggregate effect of several wind turbines should be also considered, although additional research is necessary in order to define accurate models and procedures for estimating this effect [8].

3.2.2. ATC radars

Eurocontrol, the European Organisation for the Safety of Air Navigation, and the National Telecommunications and Information Administration (NTIA), located within the Department of Commerce of the United States of America, have published some guidelines on how to assess the potential impact of wind turbines on air traffic control radars [8,9]. There are other complementary guidelines or comments published by national organisms [56,58,59]. Although they do not agree in every aspect, similar methodologies are proposed. A case by case analysis is proposed by all the involved regulatory bodies as the most appropriate method for determining the potential impact of a wind farm.

According to the guidelines of Eurocontrol and NTIA, the most critical effects in ATC radars may be the wind turbine clutter returns on radar performance, and the increasing of the effective noise floor level.

The impact of the first effect is that false targets may be generated. The strength of clutter returns are calculated by applying the basic radar equation and comparing the values to the radar receiver's sensitivity [48]. Although this simple comparison is useful for many types of radar, this is a huge simplification for a modern radar system, and internal data processing such as sliding window, MTI-MTD filtering and tracking algorithms should be considered [9].

Nevertheless, although the amplitude of clutter returns will be attenuated by signal processing techniques, the energy scattered from a turbine will increase the effective noise floor of the radar receiver, and cause some of desired targets to be lost [8,62]. Therefore, this second effect is the most limiting for radar performance. Moreover, it is a more probable effect, because when a wind turbine generates clutter returns, it will for sure increase the noise floor of the radar receiver. The criteria that can be used to calculate threshold values for this effect are given in [62].

Additionally, the effect of beam blockage should be analyzed. The shadowed volume where detection capacity may be diminished can be estimated by applying geometric criteria and power reduction threshold levels (see Fig. 6). The procedure described by Eurocontrol estimates the volume considering the geometry of the wind turbines and the transmitter, and taking into account the maximum height of the turbine, the earth curvature, the fact that the electromagnetic waves do not propagate in straight line above earth, and the difference in phase between the direct and scattered signals [9]. By contrast, the method proposed by NTIA relates the power reduction of the radar return and the relative distances between the transmitter, the turbine and the shadow volume [8].

Regarding to the type of radar, NTIA suggests analyzing the impact on Primary Surveillance Radars (PSR). With respect to the effects on Secondary Surveillance Radars (SSR), it is suggested treating wind farms as static structures, because the movement of wind turbine blades should not affect SSR performance [8]. On the other hand, Eurocontrol determines specific methods for PSR and SSR, because bearing errors may occur when there is a small path difference between the direct and reflected signals, and false targets could appear if there is a large path difference, and consequently, the assessment of false targets caused by reflections in wind turbines is proposed [9].

As a result, Eurocontrol classifies the area under analysis in zones arrangements with different affection levels, and consequently, with different analysis procedures for both types of radars:

Zone 1 – Safeguarding zone (PSR and SSR): the safeguarding zone is an initial restrictive or safeguarding region that surrounds the surveillance sensor, where no developments shall be agreed.

Zone 2 – Detailed assessment zone (PSR and SSR): following the safeguarded region, it is an area where surveillance data providers would oppose planning applications, unless they were supported by a detailed technical and operational assessment provided by the applicant, whose results are found to be acceptable to the surveillance provider.

Zone 3 – Simple assessment zone (PSR only): in this section a simple assessment of PSR performance should be sufficient to enable the surveillance data provider to assess the application.

Zone 4 – Accepted zone (PSR and SSR): beyond the simple assessment zone, there are areas within which no assessments are required and within which surveillance service providers would

not raise objections to wind farms on the basis of an impact to surveillance services.

According to this, for zones 2 and 3, an impact analysis similar to the one presented in this section should be carried out, taking into account blocking, clutter and Doppler effect issues.

As in weather radars, clutter and Doppler effects can also occur for the side lobes of the radar antenna [8]. The possible consequences in ATC radars are loss of desired targets, false target occurrences on azimuth values other than that of the wind farm, and the increase of the noise floor in the radar receiver [8]. As a consequence, the entire radiation pattern of the radar antenna should be considered in the analysis.

The aggregate effect of several wind turbines on ATC radars can be calculated, as a first approximation, as a linear combination of the effects from individual turbines [8]. However, further research is to be done in order to obtain more accurate results, mainly for considering interaction amongst turbines of a wind farm.

3.2.3. Marine radars

Interference to marine radars is primarily due to echoes from mast and nacelles of turbines, which present high RCS values. The severity of this effect depends upon the incident angle of the radar beam to the turbine [58].

3.3. Mitigation measures

The measures for mitigating the impact of the turbines on the radar performance can be focused in the design of the wind farm or in the radar segment.

If the potential impact is detected before the installation of the wind farm, locations and dimensions of wind turbines can be adapted to avoid, or at least minimize, the impairment to radars. In particular, it should be avoided that wind turbines be located in line of sight with the radar antenna. In weather radars, which have several beam elevation angles, it should be fulfilled that the blade tip on the vertical position remains below the lowest elevation angle of the radar beam. A reduction of the mast height and/or the blade length may minimize the impact. In case the previous condition cannot be fulfilled, it is recommended to situate the wind turbines so that they lie in a radial direction relative to the radar. This will minimize the radar cross section the wind farm presents to the radar beam and thus minimize the affected sector [14].

Due to the great influence of both wind farm layout and dimensions of wind turbines have on the potential impact, associations related to radar services are demanding case by case impact studies before a wind farm is installed [8–10,14,24,56,58].

On the other hand, some studies about the possibility of manufacturing stealthy wind turbines are being carried out. These studies are based on the fact that the scattering from a wind turbine can be reduced by modifying its characteristics. This can be achieved through careful shaping of the tower and nacelle to direct the radar echoes away from the radar [20,63]. Nevertheless, the blades shaped cannot be modified as they are carefully designed for maximum efficiency and aerodynamic. Therefore, a possible alternative would be coating the wind turbine blades with radar absorbing materials (RAM) in order to minimize the signal returns from them [7,20,21,63].

Once the wind farm is installed, only the identification of the echoes from wind farms within the radar results and mitigation measures in the radar segment can be applied.

The radar signatures of wind turbines can be identified on the radar display, as they have specific properties which allow the proper differentiation from desired targets. For example, in weather radars, although echoes from isolated storms are mixed with the wind turbine clutter echoes, the wind turbine signals are characterized by random radial velocity and large spectrum width, as it can be observed in Fig. 10. Nevertheless, in ATC radars sometimes it is difficult to differentiate real and false targets [58], and in any case, the strong clutter returns from the turbines hide the desired echoes from airplanes or weather phenomena in the near area of the wind farm (in the example of Fig. 10, the large spectrum widths reduce the accuracy of the Doppler velocity estimations).

In weather radars, conventional clutter filters are based on the assumption that the clutter is generated by ground, and therefore, is stationary. On the contrary, the spectral characteristics of the reflections from rotating blades can be confused with those from the desired weather signal. Consequently, filters based on spectral characteristics are mostly ineffective [64], and techniques to remove the echoes from turbines without subtracting the weather information are needed.

Current investigations in weather radars are focused on the automatic detection of wind turbine returns and the subsequent mitigation of wind turbine clutter by means of two different approaches. The first one consists of exploiting the specific Doppler spectral features of the wind turbines in order to identify if echoes from atmospheric phenomena are affected by clutter from wind turbines, and subsequently, using adaptive scanning techniques of phased-array radars and non-stationary signal processing techniques to filter the clutter out [65–68]. The second one is based on the analysis of radar data products (reflectivity, Doppler velocity, and spectrum width) to indentify the residual wind turbine clutter signals that pass though the ground clutter filter by means of different texture maps and fuzzy logic detection [69].

Advanced signal processing can be applied in order to mitigate the effect of wind turbines on ATC radars [16,61]. For example, in [70], a solution based on the combination of discrimination techniques applied at the pre-detection, detection and post detection stages of the radar signal processing chain is proposed.

Marine navigational radars are low complexity/cost and the practicality of introducing this kind of signal processing is considered unlikely [17].

Another possible solution is to use a gap infill radar (Gapfiller) that provides radar surveillance coverage for the shadowing zone which is created behind the wind farm [40]. For this purpose, the capacity of the number of radar feeds into the multi-radar tracking system needs to be increased [56]. A similar idea is commented in [41] for the case of weather radars, more precisely, the possibility of providing supplemental surface weather data transmitted automatically from the wind farm to the radar to compensate for the wind farm degraded data.

4. Aeronautical navigation systems

VOR (VHF omnidirectional radio) is a radionavigation system which enables aircrafts to determine their position and stay on course, to support both approach and departure procedures and navigation on route. VOR operational frequency band is between 108.0 and 117.95 MHz. VOR transmitters, located on the ground, radiate two VHF radio signals: a reference signal that is omnidirectionally broadcasted, and a signal of variable amplitude that sweeps around a vertical axis 30 times a second. Doppler VOR systems are based on VOR systems, but they use the Doppler shift of an electronically rotating antenna to generate the variable signal, and therefore, to improve the accuracy. The variable signal is modulated such that it is in phase with the directional signal only when detected from the north in the aircrafts. From other directions, the phase difference between the two signals indicates the receiver's bearing from the beacon [23,58].

ILS (Instrument Landing System) is a collection of radio transmitting stations used to guide aircraft to a specific airport runway for landing, especially during times of reduced visibility.

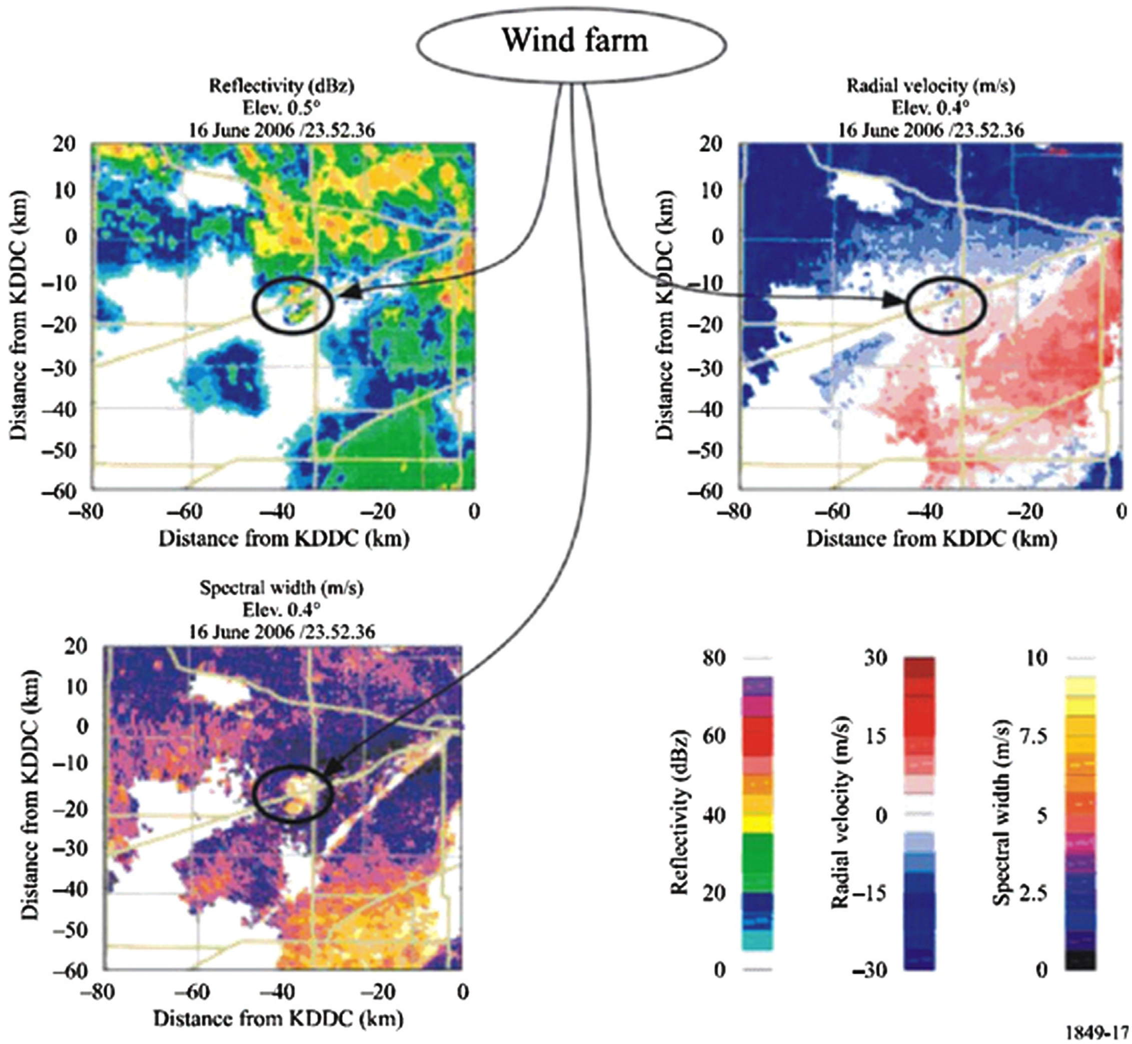


Fig. 10. Results of weather radars detection in presence of wind turbines, where echoes from isolated storms are mixed with the wind turbine clutter echoes. (*Source*: Rec. ITU-R M.1849 [49]).

Typically, an ILS includes a localizer antenna centered on the runway beyond the stop end to provide lateral guidance, a glide slope located beside the runway near the threshold to provide vertical guidance, and marker beacons located at discrete positions along the approach path to alert pilots of their progress along the glide-path and radiation monitors [23].

4.1. Interference effects of aeronautical navigation systems

For the VOR receiver on-board the aircraft, depending on the importance of the multipath, some azimuth direction shift may occur. If the total bearing error rises above 3°, the service will be no longer available [22]. Doppler VOR seems to be less susceptible to multipath interference [10,22]. For ILS systems, flight calibration results may be worsened [24].

4.2. Methodology to evaluate the potential impact of a wind farm on aeronautical navigation systems

The International Civil Aviation Organization (ICAO) defines safeguarded distances named as Building Restricted Areas (BRAs) whose shape and dimensions are dependent upon individual facility types in [10]. These protected BRAs are also applicable to the deployment of wind farms. In case of a wind farm infringing these limits, potential issues concerning wind turbines should be dealt with on a case by case basis [10,24].

The methodology to evaluate the potential impact is based on determining if the volume occupied by a specific wind turbine interferes with the clearance volume around an aeronautical navigation system. For surveillance and communication facilities it is recommended that wind turbines should be assessed at all times even outside the BRA for omni-directional facilities [10].

The Civil Aviation Authority (CAA), a public and independent specialist aviation regulator and provider of air traffic services in the United Kingdom, suggests a similar criterion not based on BRAs, but on the following rule of thumb: a wind farm whose blade tips at their maximum height are below the visual horizon when viewed from a point located 25 m above an aeronautical radio station site may be acceptable [24].

4.2.1. VOR systems

According to ICAO [10], proposed wind farms should be assessed to a distance of 15 km from the VOR facility, with special attention to any turbines within the BRA delimited by the following criteria: any turbine infringing a 600 m distance (r) or a 1° slope from the center of the antenna at ground level (α) to a distance of 3 km (R), or a 52 m horizontal surface (h) from a distance of 3 km (R) to 15 km (j). Fig. 11 shows the BRA shape for

omni-directional navigational services, such as VOR, and the dimensions of this shape for the VOR case. The heights and surfaces specified for wind turbines apply to blade tip in vertical. Where the terrain cannot be considered to be flat, for example in the case of sloping terrain, then all wind turbine proposals should be assessed out to the full radius of cylinder *j* or the BRA adapted to the actual terrain (see Fig. 11). The consultation zone of 15 km is also proposed by Radio Advisory Board of Canada (RABC) and Canadian Wind Energy Association (CanWEA) [58].

In general, within the consultation zones, computer simulations can be used to assess the effect of wind multipath caused by wind turbines on VOR systems, using worst case assumptions. However, there is no recommended methodology in order to estimate this effect, and it is necessary to consider how much degradation of performance can be allowed [10].

In practice, most cases of single wind turbine developments are acceptable at distances greater than 5 km, and wind farms of less than 6 turbines are acceptable at distances greater than 10 km from the facility. Wind turbine developments to a distance of 15 km from the facility should be analyzed, and further assessment is required for any turbine within the BRA. In cases where there are existing wind turbines within the 15 km zone, the evaluation of new proposals needs to consider the accumulative effect of all the turbines [10].

4.2.2. Instrumental Landing System

The BRAs for directional navigation facilities are adapted to the antenna radiation pattern of each system, and therefore, the BRA for ILS is different in shape with respect to the omnidirectional systems such as VOR, as it is shown in Fig. 12. The dimensions of this shape () are dependent on the specific type of ILS used, and they are outlined in [10]. In fact, aerodromes are encouraged to obtain specific criteria from the manufacturer or supplier of their equipment in order to obtain more realistic estimations of the calculation zones [24].

4.3. Mitigation measures

Due to the strategic nature of these infrastructures, no mitigation measures are considered, apart from applying the safeguarding criteria to protect the VOR and ILS radio signals from corruption [10,24,58].

5. Radiolinks

A radiolink is a telecommunication facility between two fixed points located over terrain that aims at point-to-point data transmissions by means of radio waves, featuring specified characteristics of quality and availability. Radiolinks use different frequency bands between 800 MHz and 22 GHz, depending on their data transmission capacity. Therefore, they are sometimes called microwave links [71].

5.1. Interference effects

The performance of a fixed radio link might be degraded due to obstruction or scattering of radio waves by a wind turbine and the effect of large blades rotating. Wind turbines can cause large fades in the signal received by one of the ends of the link, thus reducing the power of the received signal (obstruction), or generated interfering reflected signals that reduce the wanted-to-unwanted protection (scattering) [26]. Other effects such as near-field effects [27] are not probable in the UHF band or higher frequencies.

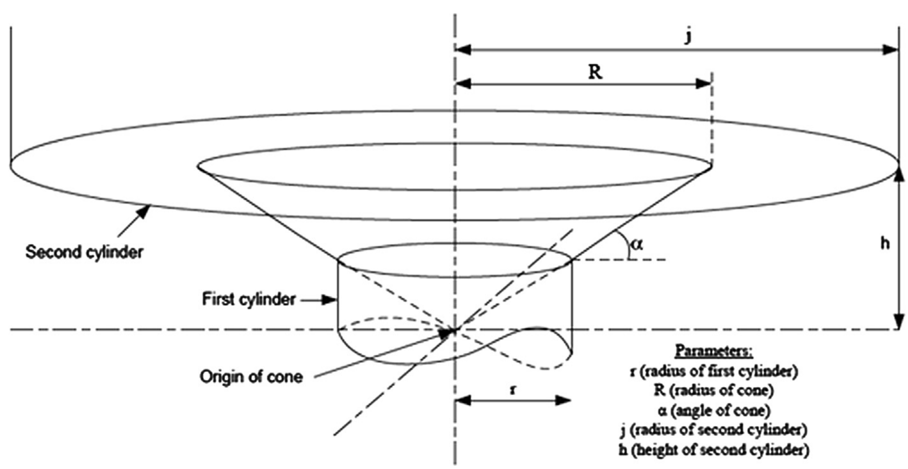


Fig. 11. Building Restricted Area for the omni-directional navigational facilities. The origin of the cone and the axis of the cylinders are located in the center of the antenna system at ground level.
(*Source*: ICAO EUR Doc 015 [10]).

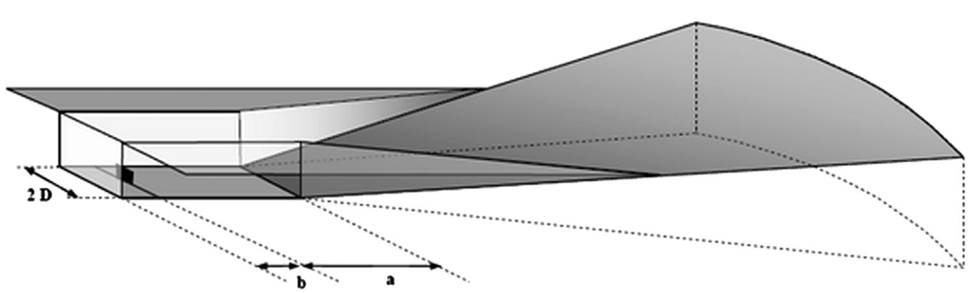


Fig. 12. Building Restricted Area for directional navigational facilities, where the antenna is represented as a black rectangle.
(*Source*: ICAO EUR Doc 015 [10]).

Therefore, two main degradation mechanisms may have an effect on a radiolink and must be considered in the impact studies: diffraction effects and reflection or scattering.

5.2. Methodology to evaluate the potential impact of a wind farm on fixed radiolinks

5.2.1. Diffraction effects

Because of the point-to-point nature of these links, and the frequency range they use, unobstructed line of sight between both ends of the links is intended. Diffraction effects occur in the forward scattering zone of the wind turbines, where the turbine obstructs the path between transmitter and receiver, located at the two end points of the link. Attenuation due to this mechanism will be of significance for high frequency links with a turbine close to one of the antennas [26].

The criterion for avoiding diffraction effects is based upon an exclusion volume around the radio path of a fixed link. In the specific case of a wind farm, an exclusion zone equal to the second Fresnel zone is proposed in [27]. The Fresnel zone takes the form of an ellipsoid with the transmitter and receiver at the foci, being the radius dependent on the working frequency. To determine if an obstruction of the Fresnel zone will exist, the volume occupied by the turbine due to the blade rotation and the rotor orientation must be considered, together with the terrain conditions. If there is no intersection between the exclusion zone and the volume occupied by the turbine, no impact due to the link obstruction is expected.

Fig. 13 shows an example of the second Fresnel zone of several radiolinks. It is clearly observed that the radiolinks depicted in green are not obstructed by the wind turbines, while the turbines intercept the second Fresnel zone of the radiolink depicted in red.

5.2.2. Reflection or scattering

A fixed radio link is designed for certain quality criterion, normally expressed as a Carrier-to-Interference ratio (C/I). The C/I is the quotient between the desired (the average received modulated carrier power) and the undesired (the average received co-channel interference power) signals. In this case, the interference is due to the signal reflected on the turbine that reaches the receiver located at the other end of the link. If the C/I ratio is lower than the threshold for good quality, link degradation may occur.

Normally a high C/I is specified, which should be exceeded for all but 20% of time, and a somewhat lower value which must be exceeded for all but a much smaller percentage of time, typically in the range 0.1–0.001% [26]. It is suggested that a C/I ratio somewhat higher than the 20% value should be taken as a reference to draw an exclusion zone around the radio path. This exclusion zone delimits the area where a wind turbine should not be installed to prevent the radiolink degradation.

To calculate this exclusion zone, the interference caused by a wind turbine should be assessed by means of the bistatic radar equation, where the wind turbine is characterized in terms of its maximum RCS [27]. In case the wind turbine causes interference, it should be moved away from the link path, in order to decrease the interference level. The proper location for the turbine to not disturb the radio link can be assessed by applying the bistatic radar equation in suitably small increments of the distance of the wind turbine to the radio path until the required value of C/I ratio is obtained [27].

5.3. Mitigation measures

As previously commented, both the results of the analysis of diffraction and scattering effects can be represented by means of exclusions zones that should be respected. If a potential affection is detected before the installation of the wind farm, some design changes can be proposed with respect to the wind turbines locations or dimensions, by mutual agreement between the service provider and the wind farm developer, in order to avoid these exclusion areas and make the coexistence between both services possible.

If the path between the two terminals is obstructed or interfered, another possible solution is to use intermediate radio link stations known as repeaters. To do so, suitably elevated positions should be selected, preferably where a telecommunication tower already exists in order to save in civil works costs. The new path profiles must meet the above-mentioned clearance criteria and be able to effectively connect the original ends of the radiolink [71].

6. Analog and digital terrestrial broadcasting services

Terrestrial television broadcasting is found in the VHF (30–300 MHz) and lower UHF (400–900 MHz) bands. At these frequencies, the transmitter antenna is usually situated at an elevated site in order to get a wide coverage area. Broadcasting networks consist of "main transmitters" of relatively high powers, supplemented by gap-filler transmitters with lower powers to provide coverage in shadowed areas (those areas shielded from the main transmitters by the terrain) [71]. These secondary transmitters are usually dependent on the main transmitters, as they re-transmit the broadcasted signal received from the primary transmitter. Consequently, if a gap-filler transmitter is located on a degraded quality zone, the re-transmitted signal will also be degraded and the potential effect of a wind farm may be even greater than the coverage area of the main transmitter itself.

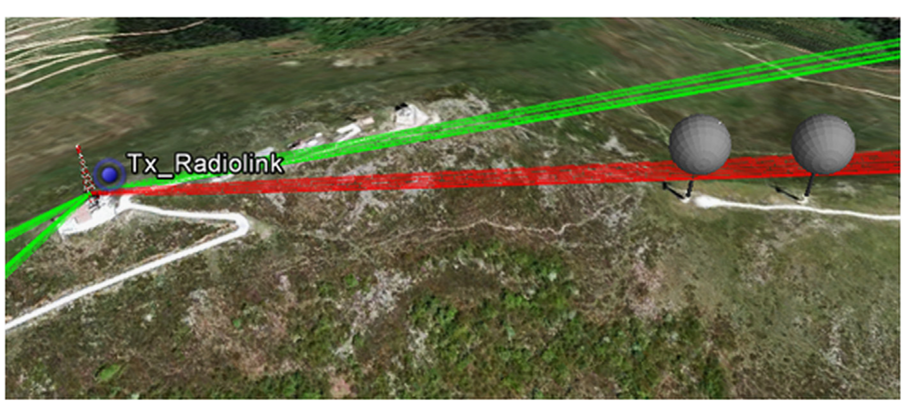


Fig. 13. Example of the exclusion volumes that should be respected to avoid diffraction effects on radiolinks [61]. The blades of the turbines are shown as spheres in order to represent the volume occupied by blade rotation and rotor orientation. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

6.1. Interference effects of a wind farm on TV services

In the case a wind farm degrades the analog television quality, secondary or ghost images are observed, which are dependent on the amplitude and the relative delay between the transmitted signal and the scattered signals. Moreover, large ghost signals with very small path differences can cause loss of color, buzz on sound, loss of detail and brightness flicker in the picture and corruption of teletext pages [33,35].

By contrast, the new digital systems feature considerable robustness against interferences. However, the performance of the different DTV standards under this specific type of time varying multipath channel is yet to be assessed, and it will depend on the modulation and channel coding schemes used by each standard [38]. In the case of DVB-T standard [72] mainly used in Europe, the presence of a wind farm might cause an increase in operational threshold parameters necessary for an optimal reception, leading to potential problems in the fringe of the coverage area [37,38]. The ATSC system [73] used in the U.S.A. has included technical advances that provide receivers able to handle strong multipath distortions. However, if the signal level variations due to a wind farm make the signal level to be below the operational threshold, the video will be affected [39]. Similar effects are expected for other systems [38], such as ISDB-T BST-OFDM [74], adopted in Japan and South America, or DMB-T [75], developed in China.

6.2. Methodology to evaluate the potential impact of a wind farm on TV services

As commented in Section 2, the effect of a wind turbine on an EM signal is different depending on the scattering region where the receiver is located, and therefore, the potential degradation on the television reception should also be analyzed separately. As a reference, it should be considered that, in the UHF band, about 80 percent of the region around the turbine is the backscattering zone, while the remaining 20 percent corresponds to the forward scattering zone [30].

6.2.1. Forward scattering region

In the forward scattering region, the transmitter, the wind turbines and the receiver are almost lined-up. In this case, the forward scattering region of the wind turbines is characterized by a shadow zone of reduced intensity behind the turbine, due to the sum of the direct field and the scattered field. The blades rotation introduces a significant and quite rapid variation on the scattered signal, and therefore, on the received signal within the forward scattered region.

The impact of this effect is very dependent on the coding algorithms and modulation schemes adopted by each standard. Hence, DVB-T system seems to have little sensitivity to degradation in this zone [38]. In contrast to this, for ATSC systems the interference seems to be stronger when the transmitted signal passes through the turbine rotating blades [76].

In order to establish the potentially affected area of each wind turbine, the shadow zone that the wind turbine creates with respect to the transmitted signal can be projected over a terrain database. This shadow zone includes all the reception locations where a turbine would be located within the transmitter-receiver path, and it will depend on the wind turbine dimensions, the relative location of the transmitter, the wind turbine and the receiver. To do so, the rotor orientation and the blades rotation should be considered. This way, the reception areas in the forward scattering region of one or more wind turbines of the wind farm can be established.

Fig. 14 shows an example of the area potentially affected by the forward scattering of a wind farm. Areas within the shadow zone of one or more wind turbines are indicated according to the color scale [61]. It should be mentioned that a methodology to estimate the signal variability due to blade rotation in the forward scattering zone has not yet been established.

6.2.2. Backscattering region

In the backscattering region, the signals scattered on the wind turbines give rise to a series of attenuated, time-delayed, and phase shifted replicas of the original signal. These scattered signals are time-varying due to the blades rotation and the changes in the rotor orientation with respect to the wind direction. The resultant propagation channel is thus characterized by a direct path from the transmitter and a time-varying multipath due to the scattered signals. This situation is graphically depicted in Fig. 15.

This phenomenon can be properly analyzed in the Channel Impulse Response, which represents the electromagnetic path between a transmitter and a receiver. Fig. 16 shows an example of the Channel Impulse Response of a reception location in the area of influence of a wind farm obtained from empirical data [38,45]. It is

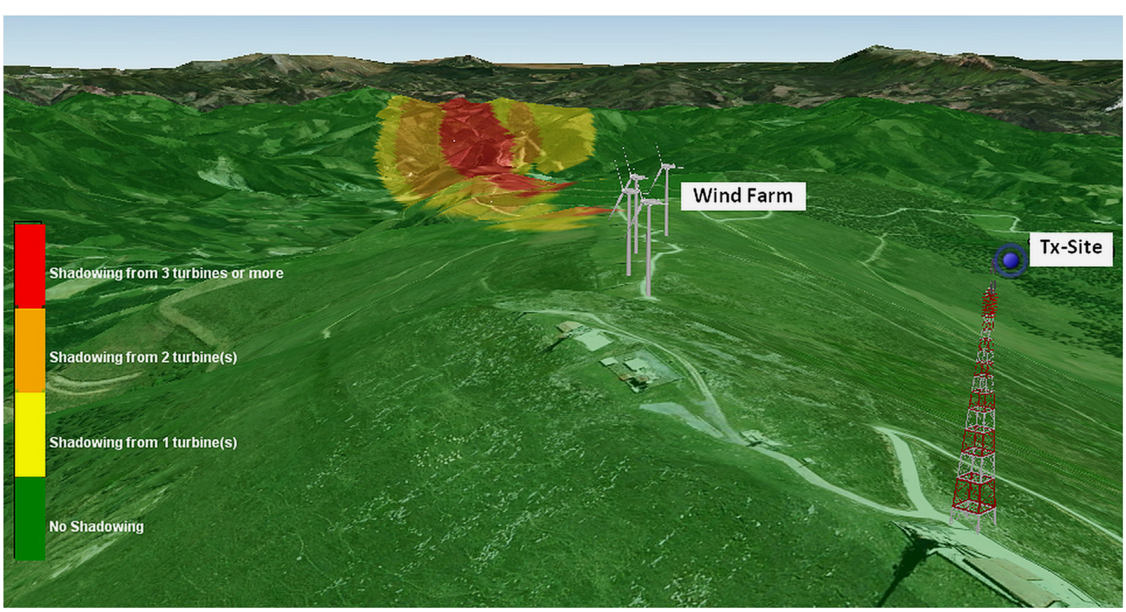


Fig. 14. Example of the shadow areas caused by a wind farm [61].

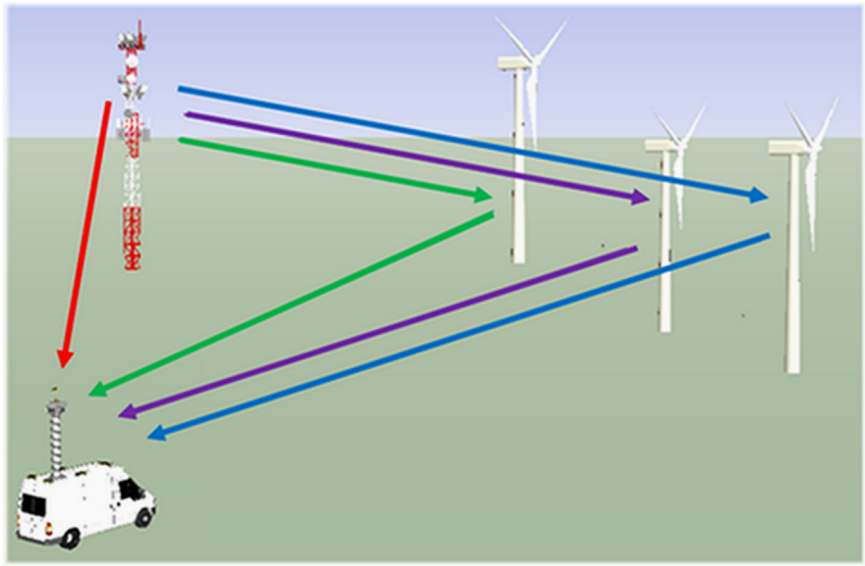


Fig. 15. Representation of the signal scattering on wind turbines leading to a time-varying multipath channel in the receiver (in this case, a measurement mobile unit).

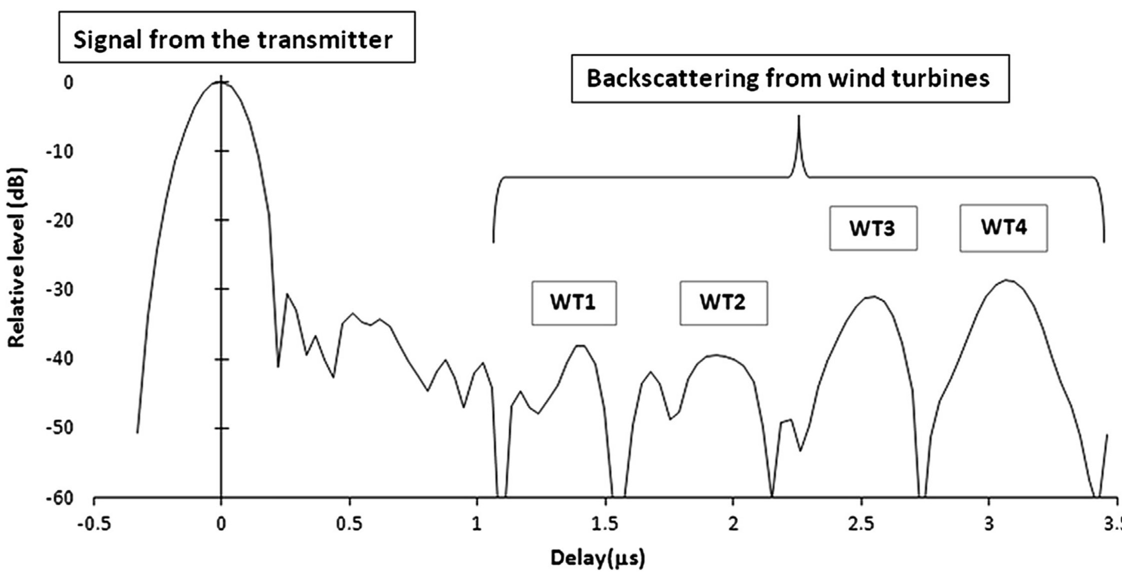


Fig. 16. Example of a Channel Impulse Response in presence of a wind farm: relative amplitude level of each component of the multipath as a function of the relative propagation delay.

composed of a direct signal coming from the transmitter and a series of multipath components due to the wind turbines. The relative delays of these delayed multipath components are proportional to the path difference between the direct signal (transmitter–receiver) and the scattered signal (transmitter–wind turbine–receiver).

6.2.2.1. Theoretical models for wind turbine scattering estimation in the UHF band. In order to estimate the relative level of the signal scattered by the wind turbines, several studies have been carried out to provide simple scattering models since the late 70 s. Some of these models were the ones proposed by Sengupta [28,31], the BBC Research Department [32,33] or Van Kats [34]. It should be considered that most of these models were proposed at an early stage of the development of the wind industry, and the wind turbine structures have dramatically evolved ever since. For example, Sengupta and Van Kats in [30] and [34] refer to two blade machines, whereas current wind turbines are normally three-blade. In [32], the support structure is said to be a large lattice or concrete tower, whereas current masts are tubular towers made of steel.

The International Telecommunication Union (ITU-R) provides in Recommendation ITU-R BT.805 a simple scattering model based on a simplified characterization of the blades, considered as flat metallic plates and oriented as to scatter the maximum signal power towards the receiver [36]. The recently approved Recommendation ITU-R BT.1893 aims to overcome some of the limitations of the Rec. ITU-R BT.805 with respect to the scattering model, using an assumption that is closer to the actual shape of the current blades and including the dependence on the wind turbine orientation against the wind [37]. However, all these models have proved to not accurately characterize signal scattering from wind turbines, due to several reasons. For example, they are merely based on the signal scattered by the blades, thus, they do not consider the contribution of the mast to the scattered signal. Nevertheless, despite being based on the scattering by the blades, they do not model the signal scattering variation due to rotation,

which may be of importance for the assessment of reception quality of the new telecommunication services in the UHF band. Moreover, they do not consider the scattering pattern variation in the vertical plane, and thus obviate the situation where a wind farm is located at a higher height than the potential viewers [45]. A new model is being developed in the University of the Basque Country in order to overcome the constraints of the above-mentioned methods [45].

6.2.2.2. Practical application of the assessment methodology in the backscattering region. For assessment purposes, the Channel Impulse Response due to signal scattering on the wind turbines of the wind farm should be estimated. In the first place, the relative delays of the scattered signals can be easily calculated from the location of the transmitter, the wind turbine and the receiver. Then, for each wind turbine, the currently available models are applied to calculate the corresponding ratio between the desired signal (coming from the transmitter) and the interfering signal (due to scattering on the wind turbine). This way, the amplitude of each of the multipath components is obtained (see Fig. 14).

This calculation should be applied to the whole coverage area. To do so, this area is normally divided into small cells forming a grid, obtaining an estimation of the Channel Impulse Response for each cell of the grid.

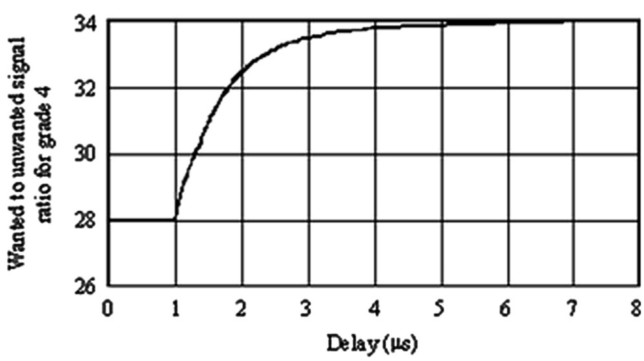


Fig. 17. Quality criterion for analog TV according to Rec. ITU-R BT.805 [36].

6.2.2.3. Impact on television quality. In order to determine if degradation could exist, a quality degradation criterion must be applied depending on the standard.

- For the case of PAL analog television, Rec. ITU-R BT.805 gives the required wanted to unwanted signal ratio as a function of the time difference between the wanted and unwanted signals (see Fig. 17). Above this threshold, the impairment would be considered as "perceptible, but not annoying" [36]. The potentially cumulative impairment caused by a multiple-machine wind turbine installation is not established in the Recommendation. Taking into account that normally a wind farm will be composed of more than a wind turbine, the above included criterion should be applied to the signal scattered by each turbine. If any of the scattered signals is above the threshold, the quality should be considered as degraded [36].
- For the case of DVB-T digital television, Rec. ITU-R BT.1893 states that the threshold Carrier-to-Noise ratio (C/N, the ratio of the received modulated carrier signal power C to the received noise power N) for Quasi Error Free reception tends to increase with the amplitude of the echoes. The time-varying nature of the multipath due to wind turbines is an additional factor that increases the required C/N threshold. According to the Recommendation, reception areas where the dynamic multipath levels are less than 25 dB below the direct signal may experience increments in the C/N threshold ratios by up to 8 dB [37,77]. This way, the C/N values before and after the installation of the wind farm can be compared. In a similar way to the Rec. ITU-R BT.805, this criterion is based on the signal scattered by one wind turbine. As a result, for a complete wind farm, the contributions from all the wind turbines should be obtained and the most critical should be taken as a reference. As this method does not consider the impact of the wind farm as a whole, for the DVB-T case, a more complete methodology was proposed in [38]. This methodology takes into account not only the multiple paths due to signal scattering on the wind turbines but also their amplitude variability as blades rotate.

It should be noted that for the case of other digital television systems, quality degradation criteria for this specific kind of interference are yet to be assessed.

Fig. 18 shows an example of the coverage area of a DVB-T transmitter potentially affected by a wind farm. Red color represents

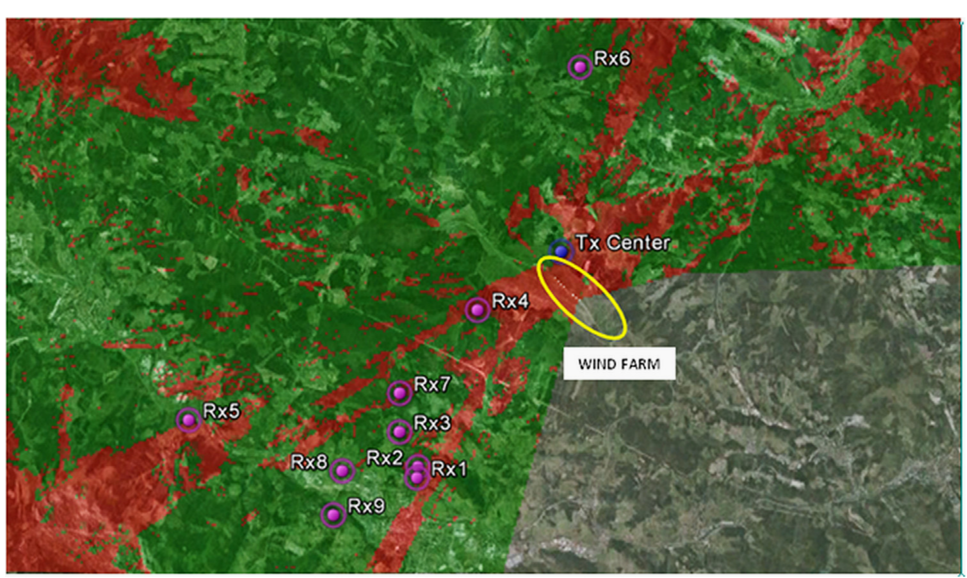


Fig. 18. Example of representation of the coverage zones that could be affected by the presence of a wind farm [61]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

zones where the C/N would be below the C/N threshold (increased by the effect of the wind farm), and green color represents the opposite. Special attention should be paid to populated areas and the location of fill-in or secondary transmitters. For this purpose, the Channel Impulse Response can be estimated for specific reception points, shown in pink in Fig. 18 [61].

6.3. Mitigation measures

As previously commented, new digital systems are considerably more robust than the analog television systems. As a result, the analog switch-off to digital standards is considerably reducing the impact of wind farms on television broadcasting.

One of the easiest mitigation measures is to improve the directivity of the receiving antenna in order to reinforce the direct signal from the television transmitter while attenuating the scattered signals from the turbines. However, this is not always enough to avoid reception problems, and in any case it is not valid in the forward scattering zone, where the wind turbines are aligned and positioned between the transmitter and the receiver.

In case of affection to a broadcasting system, a possible solution will be the installation of a new television transmitter in a transmitter site that provides good coverage, and located far from the wind farm, in order to avoid scattered signals of high amplitude.

The replacement of the off-air reception with an alternative such as satellite or cable can be also considered [35].

7. Conclusions

This paper provides a comprehensive review about the potential impact of wind turbines on the telecommunications services. It summarizes the main effects than can be observed, as well as the methodology to follow in order to determine if a problem may occur, and possible corrective measurements.

As it can be observed, there are several guidelines or handbooks about this issue. However, there is no general agreement or international statement to be applied. Moreover, these proposals are usually promoted by the affected operators, and therefore, they may be too conservatives at times.

This context leads to the necessity of carrying out further studies on this topic, in order to achieve a better characterization of the phenomena, specially aided by real measurements, and obtain harmonized protection criteria. This need is expressed by international regulation organizations such as the International Telecommunications Union [36,37], aviation regulation organizations such as the International Civil Aviation Organization [10] and Eurocontrol [9], weather and meteorological services providers such as the World Meteorological Organization [11] and Eumetnet [14], and several governmental agencies [24,58].

Even if the legal or regulation framework is not always clear, previous studies of the potential impact of a wind farm on the telecommunication services can avoid later problems which are more difficult, more time consuming and expensive than the preventive measurements that can be taken. Several software tools to apply the assessment methodologies presented in this paper are already available [61,41].

Taking this case by case analysis as a starting point, mitigation measures should be based on a coordinated and balanced approach with the objective of finding a solution that can be agreed by all parties, promoting the coexistence of the telecommunication services and the wind energy facilities.

Acknowledgment

The authors would like to thank the partners from Iberdrola Renovables for their continuous support and involvement in the study of the wind turbine effects on the radiocommunication services. Special thanks also to AEMET, Itelazpi and Abertis Telecom for their kind collaboration in this work.

This work has been supported in part by the European Union FP7 (Grant agreement no 296164), by the Spanish Ministry of Economy and Competitiveness (Project TEC2012-32370), and by the Basque Government (GIC 07/110-IT-374-07 and SAIOTEK program).

References

[1] Katsaprakakis DAl. A review of the environmental and human impacts from wind parks. A case study for the Prefecture of Lasithi, Crete. Renew Sustain Energy Rev1364-0321 2012;16(5):2850–63, http://dx.doi.org/10.1016/j.rser.2012.02.041 (online)〈http://www.sciencedirect.com/science/article/pii/S1364032112001359〉.
[2] Saidur R, Rahim NA, Islam MR, Solangi KH. Environmental impact of wind energy. Renew Sustain Energy Rev1364-0321 2011;15(5):2423–30, http://dx.doi.org/10.1016/j.rser.2011.02.024 (online).
[3] Kaldellis JK, Garakis K, Kapsali M. Noise impact assessment on the basis of onsite acoustic noise immission measurements for a representative wind farm. Renew Energy0960-1481 2012;41:306–14, http://dx.doi.org/10.1016/j.renene.2011.11.009 (online).
[4] Jago P, Taylor N. Wind turbines and aviation interests – European experience and practice. DTI; 2002.
[5] Spaven consulting, Wind turbines and radar: operational experience and mitigation measures; 2001.
[6] Poupart GJ. Wind farms impact on radar aviation interests – Final report. Quinetiq; 2003.
[7] Butler MM, Johnson DA. Feasibility of mitigating the effects of windfarms on primary radar. Alenia Marconi Systems Limited; 2003.
[8] Lemmon JJ, Carroll JE, Sanders FH, Turner D. Assessment of the effects of wind turbines on air traffic control radars, NTIA technical report TR-08-454; 2008.
[9] M. Borely, Guidelines on how to assess the potential impact of wind turbines on surveillance sensors, 2010, Eurocontrol (June).
[10] International Civil Aviation Organization, European guidance material on managing building restricted areas. ICAO EUR Doc 015; 2009.
[11] Tristant P. Impact of wind turbines on weather radars band. World Meteorological Organization. CBS/SG-RFC 2006/Doc. 3.1; 2006.
[12] Impact of wind turbines on weather radars. OPERA II WP 1.8; 2006.
[13] Vogt RJ, Crum TD, Sandifer MJB. A way forward wind farm – weather radar coexistence. NEXRAD Radar Operations Center, NOAA's National Weather Service; 2009.
[14] Finnish Meteorological Institute. EUMETNET OPERA PROGRAMME (2004–2006) – Operational programme for the exchange of weather radar information, Final report; 2007.
[15] Haase G, Johnson D, Eriksson K-Å. Analyzing the impact of wind turbines on operational weather radar products. Proc. ERAD 2010;1:276–81.
[16] Isom BM, Palmer RD, Secrest GS, Rhoton RD, Saxion D, Allmon TL, et al. Detailed observations of wind turbine clutter with scanning weather radars. J Atmos Ocean Technol 2008;26:894–910.
[17] Rashid LS, Brown AK. Impact modelling of wind farms on marine navigational radar. In: Proceedings of the 2007 IET international conference on radar systems; 2007. p.1–5.
[18] British Wind Energy Association. Investigation of technical and operational effects on marine radar close to Kentish Flats offshore wind farm, MARICO marine report; 2007. Available online: 〈http://www.bwea.com/pdf/radar/BWEA_Radar.pdf〉.
[19] Brown C, Howard M. Results of the electromagnetic investigations and assessments of marine radar, communications and position fixing systems undertaken at the North Hoyle wind farm by QinetiQ and the Maritime and Coastguard Agency. MeA report MNA 53/10/366; 2004.
[20] Rashid LS, Brown A. Partial treatment of wind turbine blades with radar absorbing materials (RAM) for RCS reduction. In: Proceedings of the fourth European conference on antennas and propagation (EuCAP); 2010. p.1–5.
[21] Rashid LS, Brown AK. Radar cross-section analysis of wind turbine blades with radar absorbing materials. In: Proceedings of the 2011 European radar conference (EuRAD); 2011. p. 97–100.
[22] Morlaas C, Fares M, Souny B. Wind turbine effects on VOR system performance. IEEE Trans Aerosp Electron Syst 2008;44(4):1464–76.
[23] Kayton M, Fried WR. Avionics navigation systems. John Wiley & Sons; 1997.
[24] United Kingdom Civil Aviation Authority. CAP 670 ATS safety requirements; 1998. Available online: 〈http://www.caa.co.uk/docs/33/CAP670.pdf〉].
[25] OFCOM. Tall structures and their impact on broadcast and other wireless services; 2009.

[26] Randhawa BS, Rudd R. RF measurement assessment of potential wind farm interference to fixed links and scanning telemetry devices, Ofcom report 2008-0568; 2009.
[27] Bacon DF. Fixed-link wind-turbine exclusion zone method. OFCOM; 2002.
[28] Sengupta DL, Senior TBA. Electromagnetic interference to television reception caused by horizontal axis windmills. Proc. IEEE 1979;67(8).
[29] Sengupta DL, Senior TBA. Wind turbine generator sitting handbook, Technical report no. 2. University of Michigan; 1979.
[30] Spera DA, Sengupta DL. Equations for estimating the strength of TV signals scattered by wind turbines, NASA contractor report 194468; 1994.
[31] Sengupta DL, Senior TBA. Electromagnetic interference from wind turbines. Wind turbine technology. Fundamental concepts of wind turbine engineering. New York: ASME Press; 1994; 447–86 (Chapter 9).
[32] Eaton JL, Black RI, Taylor GH. Interference to television reception from large wind turbines, BBC RD 1983/2. BBC Research Department, Engineering Division; 1983.
[33] Wrigth DT. Effects of wind turbines on UHF television reception, BBC RD 1992/7. BBC Research Department, Engineering Division; 1992.
[34] Van Kats PJ, Pager OPE. Reflections of electromagnetic waves by large wind turbines and their impact on UHF broadcast reception, Report 511 TM/84. British Library; 1984.
[35] Levent M., Munro I. Effects of windmills on television reception, CBC technology review; 2006.
[36] International Telecommunication Union, Rec. ITU-R BT.805. Assessment of impairment caused to television reception by a wind turbine; 1992.
[37] International Telecommunication Union, Rec. ITU R BT.1893. Assessment of impairment caused to digital television reception by a wind turbine; 2011.
[38] Angulo I, de la Vega D, Grande O, Cau N, Gil U, Yiyan Wu, Guerra D, Angueira P. Empirical evaluation of the impact of wind turbines on DVB-T reception quality. IEEE Transactions on Broadcasting 2012;58(1):1–9.
[39] Polisky Lester E. Post digital television transition - the evaluation and mitigation methods for off-air digital television reception in-and-around wind energy facilities, Comsearch Whitepaper, TP-103160.1-EN; 2009. Available online: www.comsearch.com.
[40] Aarholt E, Jackson CA. Wind farm Gapfiller concept solution. In: Proceedings of the 2010 European Radar Conference (EuRAD); 2010. p.236–9.
[41] VINDRAD. Project report v1.0, A tool for calculation of interference from wind power stations to weather radars; 2011.
[42] Stuteley G, Watson M. A method for the assessment of predicted impact by wind turbines on wireless telemetry, alleviating and mitigating infringement issues for the developer. EWEC; 2010.
[43] Knott EF, Shaeffer JF, Tuley MT. Radar cross section. SciTech Publishing; 2004.
[44] Jenn DC. Radar and laser cross section engineering. 2nd editionAmerican Institute of Aeronautics and Astronautics, Inc; 2005.
[45] Angulo I, et al. An empirical comparative study of prediction methods for estimating multipath due to signal scattering from wind turbines on digital TV services. IEEE Trans Broadcast 2011;57(2):195–203.
[46] Kohn G. The IEEE Standard Dictionary of Electrical and Electronics Terms. 6th ed.Inst of Elect & Electronic; 1997.
[47] Rinehart RE. RADAR for meteorologists. 3rd ed.Rinehart Pub; 1997.
[48] Skolnik MI, editor. McGraw-Hill; 2008.
[49] International Telecommunication Union, Rec. ITU-R M.1849. Technical and operational aspects of ground-based meteorological radars; 2009.
[50] International Telecommunication Union, Rec. ITU-R M.1464-1. Characteristics of radiolocation radars, and characteristics and protection criteria for sharing studies for aeronautical radionavigation and meteorological radars in the radiodetermination service operating in the frequency band 2700–2900 MHz; 2003.
[51] International Telecommunication Union, Rec. ITU-R M.1638. Characteristics of and protection criteria for sharing studies for radiolocation, aeronautical radionavigation and meteorological radars operating in the frequency bands between 5250 and 5850 MHz; 2003.
[52] Gallardo-Hernando B, Muñoz-Ferreras JM, Pérez-Martínez F, Aguado-Encabo F. Wind turbine clutter observations and theoretical validation for meteorological radar applications. IET Radar, Sonar Navig 2011;5(2):111–7 (February).
[53] Rabijns D. Real examples of impact of wind turbines on radar operations, Sustainable energy – sustainable surveillance workshop (organized by Eurocontrol). Belgium; 2010. Available online: ⟨http://www.eurocontrol.int/events/sustainable-energy-sustainable-surveillance⟩.
[54] Collard B. – DSNA/DTI. Example of PSR simple Assessment, Sustainable energy – sustainable ATC surveillance workshop. Brussels: Eurocontrol; 2010.
[55] Office of the Director of Defense Research and Engineering, U.S. Department of Defense. The effect of windmill farms on military readiness, Report to the Congressional Defense Committees; 2006.
[56] Kelly B. Mitigating the effects of wind turbines on NATS En-Route Ltd. (NERL) operations. National Air Traffic Services; 2011 (January).
[57] IEEE standard definitions of terms for radio wave propagation. IEEE Std 211-1990; 1991.
[58] Poirier R. RABC and CanWEA, Technical information and coordination process between wind turbines and radiocommunication and radar systems; 2009. Available online: ⟨http://www.rabc-cccr.ca⟩.
[59] Civil Aviation Authority. CAA policy and guidelines on wind turbines; 2010.
[61] de la Vega D., Fernandez C., Grande O., Angulo I., Guerra D., Wu Y., et al. Software tool for the analysis of potential impact of wind farms on radiocommunication services. In: Proceedings of the 2011 IEEE international symposium on broadband multimedia systems and broadcasting (BMSB); 2011. p.1–5, 8–10.
[62] Sanders FH, Sole RL, Bedford BL, Franc D, Pawlowitz T. Effects of RF interference on radar receivers, NTIA report TR-06-444; 2006.
[63] Pinto J, Matthews JCG, Sarno GC. Stealth technology for wind turbines. IET Radar, Sonar and Navigat 2010;4(1):126–33.
[64] Palmer R, Torres S. Phased array radar studies. Final report, National Severe Storms Laboratory, Atmospheric Radar Research Center; 2009. Available online: ⟨http://www.ofcm.noaa.gov/wg-mpar/references/NSSL-DHS_Wind_Farm.pdf⟩.
[65] Hood KT, Torres SM, Palmer RD. Automatic detection of wind turbine clutter using doppler spectral features. In: Proceedings of the 34th conference on radar meteorology; 2009.
[66] Hood K, Torres S, Palmer R. Automatic detection of wind turbine clutter for weather radars. J Atmos Ocean Technol 2010;27:1868–80.
[67] Nai F, Palmer R, Torres S. Wind turbine clutter mitigation using non-stationary signal processing methods. In: Proceedings of the 6th European conference on radar meteorology and hydrology (ERAD); 2010.
[68] Nai F, Palmer RD, Torres SM. Range-doppler domain signal processing to mitigate wind turbine clutter. In: Proceedings of the 2011 IEEE radar conference; 2011. p. 841–5.
[69] Cheong BL, Palmer R., Torres S. Automatic wind turbine identification using level-II data. In: Proceedings of the 2011 IEEE radar conference; 2011. p. 271–5.
[70] Sergey L.,Hubbard O., Ding Zhen, Ghadaki H., Wang Jian, Ponsford T. Advanced mitigating techniques to remove the effects of wind turbines and wind farms on primary surveillance radars. In: Proceedings of IEEE radar conference, RADAR '08; 2008. p.1–6.
[71] Tozer EP. Broadcast engineer's reference book. Elsevier/Focal Press; 2004.
[72] Digital video broadcasting (DVB). Framing structure, channel coding and modulation for digital terrestrial television, ETSI EN 300 744 V1.6.1; 2009.
[73] A/53: ATSC digital television standard, parts 1–6; 2007.
[74] Transmission system for digital terrestrial television broadcasting. ARIB STD-B31 Ver.1.6; 2005.
[75] Digital audio broadcasting (DAB). Data broadcasting – MPEG-2 TS streaming, ETSI TS 102 427 V 1.1.1; 2005.
[76] van den Berg J. Wind turbines and interference to broadcast signals; 2012. Available online: ⟨http://www.broadcastwind.com⟩.
[77] International telecommunication unión. Report ITU-R BT.2142, The effect of the scattering of digital television signals from a wind turbine; 2010.
[78] Agencia Estatal de Meteorología, ⟨http://www.aemet.es⟩; [last access 25.05.12].